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Procedia Earth and Planetary Science 14 (2015) 220 – 227

Procedia
Earth and Planetary Science

2nd International Seminar on Ocean and Coastal Engineering, Environment and Natural Disaster Management, ISOCEEN 2014

Dynamic Response Analysis on Submerged Floating Tunnel due to Hidrodynamic Loads

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Abstract

This paper presents mooring system analysis on submerged floating tunnel (SFT) with a number of mooring configurations and the influence of mooring angle variations to its dynamic response. Working loads considered on the tunnel are current and wave loads. The tunnel structure is assumed of steel tube with 150 m length and 5 m of diameter. Mooring configurations used are varied with 12, 16, 20 and 28 lines, with mooring angle respective to the vertical line are 30, 45 and 60 degrees. The structure was numerically modeled and the results showed that the biggest tension of 241.53 tons occurred for the case of wave heading 45 degree, 30 degree mooring inclination and with 28 mooring lines. This case generated large lift force so that a very high lines tension occurred.

Peer-review under responsibilty of the Department of Ocean Engineering, Institut Teknologi Sepuluh Nopember.

*Keywords: Submerged Floating tunnel (*SFT), Mooring System, Mooring Inclination Angle, Mooring Tension.

1. Introduction

Developing of transportation system has significantly increasing and among them is development of Submerged Floating Tunnel (SFT). Several countries have developed SFT such as Italy (Messina Straits), Norway (Hogsford Crossing), USA, UK, Netherlands and Japan (Kunisu et al., 1994)[1]. The concept of SFT developed in Japan (Hokkaido Funkawan Bay) in 1990[2] is a SFT for deep water type (100 m) with modification in two diameter design 11.4 m and 23 m. The SFT has cylinder, ellipse and polygonal structural shapes with 34 km in length.

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Peer-review under responsibilty of the Department of Ocean Engineering, Institut Teknologi Sepuluh Nopember.
doi:10.1016/j.proeps.2015.07.105

The SFT[3] or also to be called Archimedes Bridge, the idea is a tunnel which floating in the water by using Archimedes principle to support the weight of the tunnel. Mooring system is applied to keep vertical and horizontal stabilities. A SFT is an underwater tube submerged at a particular depth which is used as inter island transportation system for road or rail way. Several important aspects in SFT application are dynamic approaches, safety aspect, operational and maintenance beside specific problems such as related to mooring tension, anchor system, shore connection, earthquake and tidal waves. The SFT has small impact to the environment since it is floating in the water, and built in modular system which is can be built in for quite long distance.

The objective of this paper is to analyse SFT's mooring system effective design in accordance of environment condition so it stay in structural failed safe margin. And the recommendation to prevent such prefail can be proposed. The analysis main problem is response pattern due to marine loading at structure stresses which is focused in SFT dynamic responses in Seribu Island.

2. Methodology

2.1. Structural dynamic analysis

According to Chakrabarti (2004)[4] there are two basic approaches that must be considered for floating structure, frequency domain and time domain. Frequency domain use for solve simple problem, in general. Attain by differential equation. But this method only work for linear equations, all non – linear equations must be converting to linear. That's the limitation from this method. As for the time domain use numerical integral for equation from all non - linear systems. Examples from this equation are drag force, mooring force and damping viscosity. In API RP 2T. 1987, structural dynamic analyses for offshore structure are: frequency domain analysis and time domain *analysis*. Frequency domain analysis a simulation of the events in each time by frequency interval. Frequency domain can also be used to predict discrete waves response including platform movement. The upper hand of this method is saving calculation time. Data and result (input/output) used more often by designer. All non – linear equations must convert to linear equation. Time domain analysis dynamic structure analysis by time domain function. This method use time integral procedure and resulting time history x(t) dynamic analysis of the structure is to have data due to responses occurred, stress and or deformation or displacement. This analysis displacement response caused by current and fluid loads. Dynamic load in this analysis is random load which is not regularly varies by time. Periodically load in this analysis is current hydrodynamic load. Hydrodynamic loads on this structure are drag, inertia, and lift forces.

Lagrange theorem used for methods. Lagrange equation for Assumed Mode Method[5] with below equation:

$$v(x,t) = \sum_{i=1}^{N} \psi(x)_i u(t)_i \text{ - for NDOF System} \tag{1}$$

where: $v(x,t)$ = *displacement*
$\psi(x)$ = *shape function*
$u(t)$ = *generalized displacement*

Global assumed mode method, each $\psi_i(x)$ represent displacement shape for all structure model NDOF (N- *degree of Freedom*).Determined by system term condition $\psi_i(x)$ were:

- Form one set that un free linearly
- Must non dimensional
- Each $\psi_i(x)$ must have derivatives until such degree in V.
- Must have boundary condition (displacement), so called admissible function.

3. The Model Data

The SFT model is assumed to be submerged at 10 to 15 m under the water surface and operated in Kepulauan Seribu water with water depth of 20 m. Environmental data for the analysis consist of wave, wind and current data for 10 years return period. The wave data including significant wave height, maximum wave height, peak period, and current speed at each water depth as can be seen in Table 1.

Table 1. Environmental Data

Wave data	
Wave type	Stoke Orde 5
Wave height (H)	5.08 m
Wave period (T)	9.08 S
Wind data	
Wind speed	20 m/s
Current data	
Depth (m)	Speed (m/s)
0	1.2
1	1.192
2	1.183
3	1.174
4	1.164
5	1.154
6	1.144
7	1.132
8	1.121
9	1.108
10.5	1.094
11	1.087
12	1.063
13	1.045
14	1.026
15	1.003
16	0.978
17	0.947
18	0.909
19	0.858
20	0.777

Dimensions of the SFT main structure with 150 m length, 5 m diameter, and 12 mm wall thickness. The material properties of the SFT tube are material type of HY-80, density of 7833.41 kg/m3, Young's Modulus of 2.07E+11 Pa and Poisson's ratio of 0.3. Mooring System data consist of: Type of mooring line is wire rope (IWRC) with diameter of 90 mm, break load of 523 tonnes, weight in air of 0.032 tonnes/m, and weight in air 0.028 tonnes/m.

4. Modelling

After calculate hydrodynmaic load and hydrodynamic coefficient parameters, develop model in order to do numerical model in hydrodynamical software. Equation approcah by using previous research on SFT. During Hydrodynamic approach modeling, structure modeled as mooring floating object with draft. Assumed as fixed support at each ends of the structure. Cylindrical cross section, with water plan projection area which has hydrodynamic coefficient and motion character of hollow object. Environmental load with Stokes 5th order wave theorem and current loads with sea beda bathymetry. Simulation done based on environmental heading.

Model analysis done for 4 heading environment they are; 45 deg, 90 deg, 135 deg dan 180 deg. For mooring configurations based on inclination angle (the angle are between mooring lines and vertical lines) application can be seen on Fig. 1, and the moring lines configuration can be seen on Fig. 2.

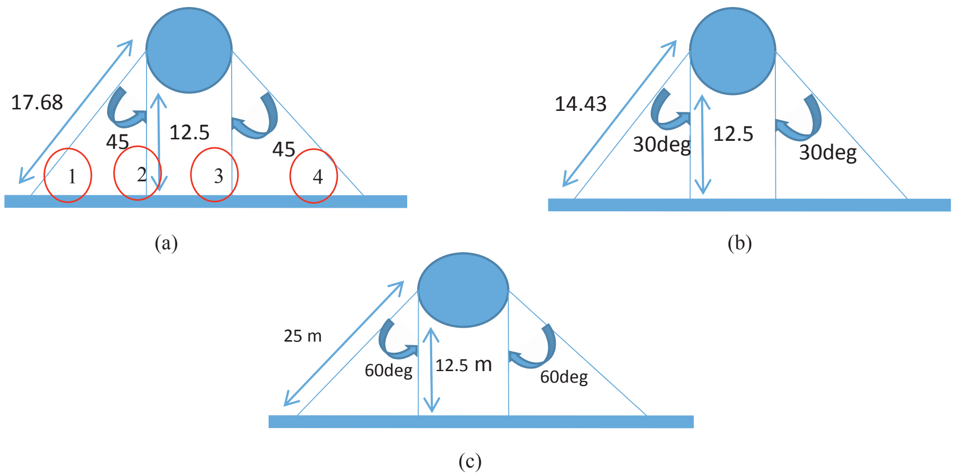

Fig. 1. Cross section of the model with various mooring inclination angle: (a) 45 deg, (b) 30 deg, (c) 60 deg

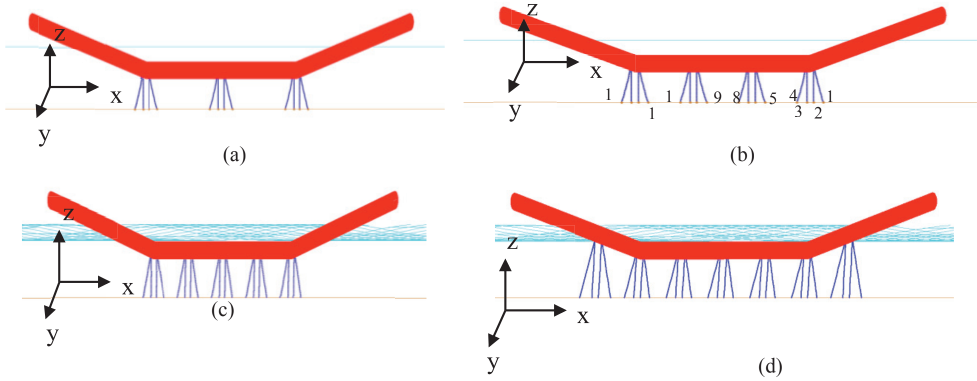

Fig. 2. Longitudinal view of the model with various mooring lines configurations: (a) 12 lines, (b) 16 lines, (c) 20 lines, (d) 28 lines.

5. Results and Discussion

5.1. Mooring Tensions

Result from the simulation is tension distribution occurred in structure due to mooring where environmental load applied. Next step after hydrodynamci modeling is calculate response due to fluid which is influenced by wave fluids surrounding and fluids current in axial, vertical and transfersal.

This modelling use – 10 until 60 seconds which discretization with inner and outer simulation time, inner and outer time will recommend by Hydrodynamic approach. After all parameters being set, run simulation for static analysis in order to attain equilibrium state. When this condition is attained, dynamic analysis can be run. Dynamic analysis results in Hydrodynamic approach are modal periods and frequency, tension on the SFT structure, environmental load time domain and SFT motion coordinate system in 6 DOF. The result recorded in table 2.

Table 2. Result of Hydrodynamic Load

Wave direction.	Case	Max *Tension* (Te)	Line	Offset (m)	
				X	Y
45 deg	30 Deg *Mooring* 12 *Lines*	196.641	LN 2	0.208	1.977
	30 Deg *Mooring* 16 *Lines*	207.994	LN 2	0.322	0.642
	30 Deg *Mooring* 20 *Lines*	233.287	LN 18	0.101	0.936
	30 Deg *Mooring* 28 *Lines*	241.526	LN 18	1.172	0.022
	45 Deg *Mooring* 12 *Lines*	224.111	LN 2	0.338	0.202
	45 Deg *Mooring* 16 *Lines*	206.614	LN 2	1.015	0.678
	60 Deg *Mooring* 16 *Lines*	204.541	LN 2	0.106	-0.87
90 deg	30 Deg *Mooring* 12 *Lines*	61.322	LN 1	0.23	0.129
	30 Deg *Mooring* 16 *Lines*	17.482	LN 3	0.389	0.007
	30 Deg *Mooring* 20 *Lines*	39.281	LN 1	0.236	0.089
	30 Deg *Mooring* 28 *Lines*	39.56	LN 28	0.144	0.052
	45 Deg *Mooring* 12 *Lines*	106.3	LN 11	0.498	0.223
	45 Deg *Mooring* 16 *Lines*	14.183	LN 15	0.26	0.068
	60 Deg *Mooring* 16 *Lines*	22.485	LN 15	0.442	0
135 deg	30 Deg *Mooring* 12 *Lines*	37.251	LN 1	0.311	0.078
	30 Deg *Mooring* 16 *Lines*	44.43	LN 16	0.286	0.096
	30 Deg *Mooring* 20 *Lines*	46.232	LN 1	0.231	0.103
	30 Deg *Mooring* 28 *Lines*	25.481	LN 28	0.26	0.03
	45 Deg *Mooring* 12 *Lines*	55.848	LN 12	0.351	0.059
	45 Deg *Mooring* 16 *Lines*	35.672	LN 1	0.286	0.051
	60 Deg *Mooring* 16 *Lines*	28.76	LN 16	0.379	0.046
180 deg	30 Deg *Mooring* 12 *Lines*	52.896	LN 1	0.283	0.112
	30 Deg *Mooring* 16 *Lines*	53.261	LN 1	0.287	0.108
	30 Deg *Mooring* 20 *Lines*	51.536	LN 1	0.258	0.11
	30 Deg *Mooring* 28 *Lines*	26.897	LN 21	-0.02	0.04
	45 Deg *Mooring* 12 *Lines*	38.65	LN 12	0.368	0.053
	45 Deg *Mooring* 16 *Lines*	39.686	LN 1	0.275	0.063
	60 Deg *Mooring* 16 *Lines*	32.981	LN 1	0.052	0.061

Table 2 is resuming of simulation in Hydrodynamic approach. From those data we can see that each tension have different value for each cases. This value influenced by mooring configuration, mooring lines angle in respective to sea bed, environmental load and its orientation direction. From table also found the biggest tension for heading 45 deg. is 241.526 tons with mooring 30 deg and 28 mooring lines occurred in mooring number LN 18, the location of this mooring number is at the edge SFT, close to bending structure. On that position experienced 1,172 m shear on x direction and 0,022 m on y direction. Minimum tension for same heading is 196.641 tons with mooring configuration 30 deg. and 12 mooring lines. The location is at LN 2 which is located at the bending edge of SFT. LN 2 experienced shear 0,208 in x direction and 1,977 in y direction.

As we know the biggest tension occurred in heading 45 deg, 241.526 tons. According to design criteria in API RP2SK for mooring, safety factor (SF) > 1.67. Safety break line for mooring line type is 313 tons, so structure is safe since the biggest tension occurred is 241,526 tons.

Correlation between mooring angles in respective of sea bed with number of mooring lines can be seen in Fig 3. Fig 3 describe tension occurred due to those correlation in heading 90 deg. with 16 mooring lines. It is shows the trend line for tensions chart each angle are similar one and another. Highest tension value occurred at angle 60°, while smallest tension occurred at angle 45°. Can be said that angle 45° has better stability than the others due to smaller lines resistance.

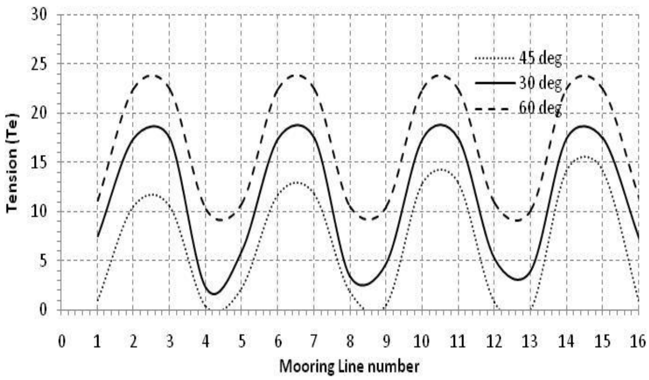

Fig. 3. Tension in 16 Mooring Lines configuration (Heading 90deg)

Fig. 4 is correlation between the configuration of mooring lines number in 45° and heading with 30° angle. It shows that tension values for 28 mooring lines configuration are the highest. Tensions for 16 mooring lines are smaller than 28 mooring lines. A tension is in proportion with the number of mooring lines. Smallest tension occurred in 12 mooring lines. This analysis use heading 45° since those all tensions average is higher than another heading in average. Almost in all cases, heading 45° tensions are more than 100 tons, so the conclusion to these cases is maximum load occurred at 45° from structure orientation.

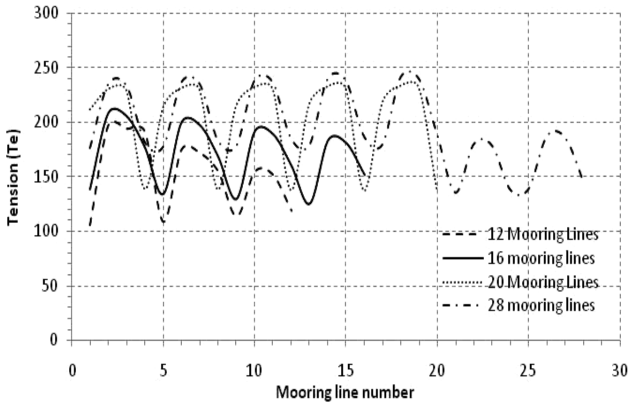

Fig. 4.Tension Hydrodynamic approach for heading 45°with 30°angle

5.2. Motion of SFT

To make the simpler modelling, continuous model used with each system assumed as independent system. Review only on axial and transversal motion. While meetings with next segmen reviewed as support or pillar. Only underwater structure will be analyzed in this analysis, which is 60 m length horizontally. Placing assumed as real structure condition. Mooring lines assumed as a spring which is put force to structure wall.

From Fig 5., axial motion of SFT heading 45°, with 30° angle and 28 mooring lines configuration has maximum magnitude 0,36 m. Those chart is time domain chart using 60 second time. From this analysis found that the magnitude is still within limit and in accordance with rule for bridge with moving load must < L/10

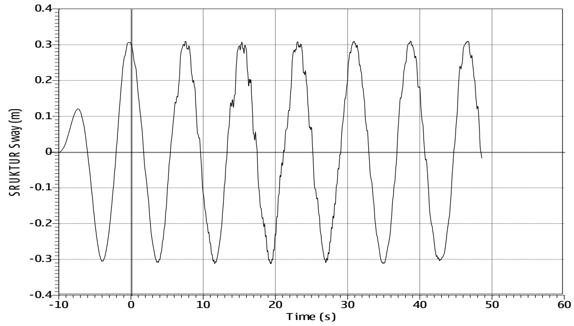

Fig 5. Axial motion response Heading 45°, 30°angle, mooring 28 lines

Transversal motions of SFT have different pattern with axial motion. In this section, similar approach with axial motion will be used to explain transversal motion response. Same case heading 45°, 30° angle with 28 mooring lines will be used as modelling analysis. From Fig. 6 shows the result of transversal motion response is harmonic motion with same frequency. Biggest magnitude is 0.012 m and this condition is still within the safety limit.

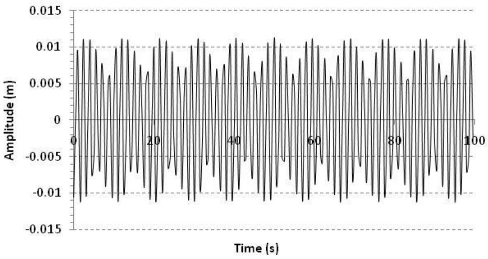

Fig 6. Transversal motion response Heading 45°, 30°angle, mooring 28 lines

6. Conclusion

Based on simulation, calculation and analysis it can be concluded as follow:

1. Review on strength calculation based on ships structure class, safety limit of SFT structure is still within tolerance.
2. Maximum tension 241,526 tons occurred at *heading* 45°, 30° angle with 28 mooring lines configuration in mooring number LN 18. Located at the edge of SFT, near to bend portion of the structure. Experienced shear 1,172 m on x direction and 0,022 on y direction.
3. Maximum magnitudes of motion for *heading* 45°, 30° angle with 28 mooring lines configuration are 0,36 for axial motion, 0,012 for transversal motion and 0.8 m for transversal motion
4. Maximum stress *heading* 45°, 30° angle with 28 mooring lines configuration is 155,956 MPa

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